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HYDROGEN APPLICATIONS SEGMENTATION & HIERARCHY

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Background

India is the third-largest energy consumer in the world behind China and the United States. Commensurately, India also experiences the largest increase in energy demand by any country, driven primarily by increasing disposable income and growing aspirations. India has about 416 GW of installed electricity capacity, and about 50% of it is powered by coal-fired plants. Of the total installed electricity capacity, only about 41% is based on renewable energy (*Power Sector at a Glance All India*, 2023). Around 47% (see Figure 1 for details) of the country's total energy need is met by coal (*Energy Statistics India*, 2023).

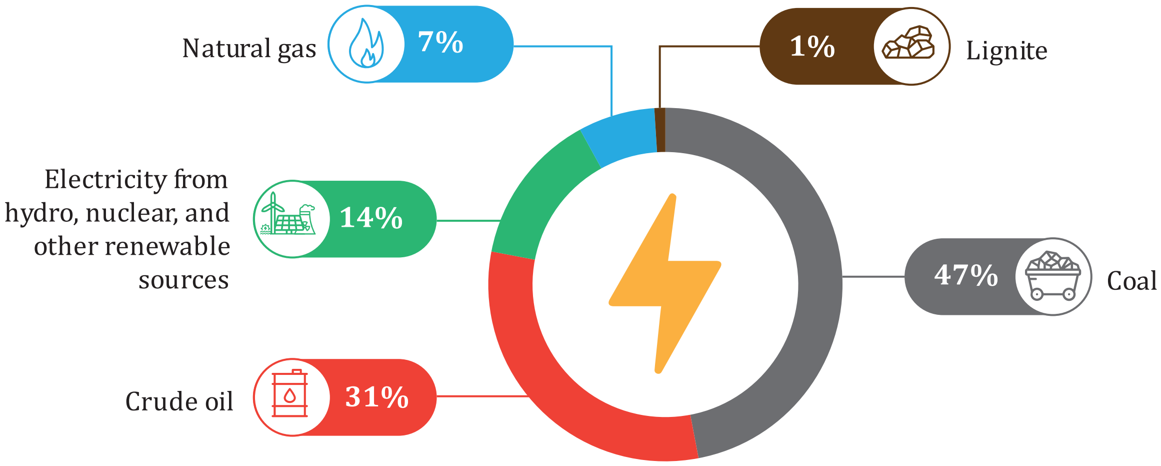


Figure 1: Source-wise energy consumption in India

In addition to coal, some of the major fossil-based primary energy sources used in India to meet the energy demand are oil, natural gas, and solid biomass (firewood). The dependency on coal, natural gas, and oil is contributing to the emissions of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane, and nitrous oxide (N_2O) into the atmosphere during the devolatilisation of coal and upon combustion of carbonaceous fuels. These are a direct cause of the rise in temperature globally. Even though India's per capita CO_2 emissions are only about 1.9 t (Ritchie et al., 2020), the adverse effects of climate change and global warming are impacting livelihoods across the country.

India's decarbonisation strategies and challenges

To reduce its reliance on non-renewable energy sources and to ameliorate the detrimental impacts of climate change, India has significantly enhanced its climate goals by setting up targets such as increasing its energy dependence on renewables to 50%, reducing carbon emissions by one billion tonnes by 2030, and achieving net zero by 2070 (*India's Stand at COP-26*, 2022). Rapid decarbonisation across sectors is essential to achieve these Nationally Determined Contributions (NDCs). Apart from increasing the share of renewables to meet the energy demand, there is also a need to minimise or mitigate the accompanied emissions from several sectors, such as transportation, industry, and agriculture.

Despite the growing popularity of direct electrification in various fields, several sectors—such as iron and steel, cement, refinery, and petrochemicals—pose a significant challenge to electrification because of the inherent chemistry of certain unit operations in the process. Other energy-intensive sectors such as long-haul heavy transportation and aviation are currently reliant on fossil fuels because of the limited availability of technologies that enable the direct use of electricity until significant improvements are brought into the energy storage density of batteries. Consequently, researchers and industry experts (Chen et al., 2022; Hertwich et al., 2019) have been exploring alternative options that are both practical and readily deployable. Among the potential solutions, hydrogen has garnered significant attention as it is being considered for a range of applications across different sectors globally.

Hydrogen: Properties and possibilities

Hydrogen is the lightest and most abundant element in the universe. It possesses a unitary energy content of approximately 120 MJ/kg, which is three times greater than gasoline (44 MJ/kg) and four to five times greater than coal (25–35 MJ/kg). As a clean fuel, its combustion product is water, and it can be combusted directly with oxygen or utilised electrochemically within a fuel cell to generate energy. Furthermore, hydrogen is an exceptional reducing agent that has several applications both as feedstock and fuel. However, it should be acknowledged that most of the hydrogen that is currently used is obtained from fossil fuels that are carbonaceous in nature.

Hydrogen is classified based on its manufacturing process. For instance, green hydrogen is produced by the electrolysis of water using renewable energy sources, while grey hydrogen is obtained through steam methane reforming (SMR). Blue hydrogen, on the other hand, is manufactured through the SMR process with carbon capture technology to capture CO_2 emissions. Most of the hydrogen that is produced in India is grey hydrogen and captive in nature (consumed at production sites). This is on account of the accompanying difficulties to store and transport hydrogen because of its low density and difficulty of liquefaction (the critical temperature of hydrogen is -239.95 ^{0}C).

Apart from this, even though the gravimetric energy density of hydrogen is three times higher than gasoline, its volumetric energy density is only about one third of the same, making it a challenge to be stored and used as a fuel. The production of hydrogen via the SMR route is deemed dirty (9.3 kg carbon dioxide emitted for every kg of hydrogen produced; Erbach & Jensen, 2021), while green hydrogen production utilising electrolysers can be expensive because of the use of critical raw materials such as platinum and rubidium in its manufacturing. Blue hydrogen requires additional carbon capture, utilisation, and storage (CCUS) infrastructure, which is used to capture the CO_2 released during the SMR process to obtain clean hydrogen, thereby increasing cost.

Despite being an expensive alternative today, its heterogeneity in application allows hydrogen to be used as a crucial tool towards decarbonisation. Its potential is recognised worldwide as it can be used in several applications such as the reduction of ores (haematite, magnetite, etc.); cement manufacturing; and fuel for vehicles, petrochemicals, and fertilisers.

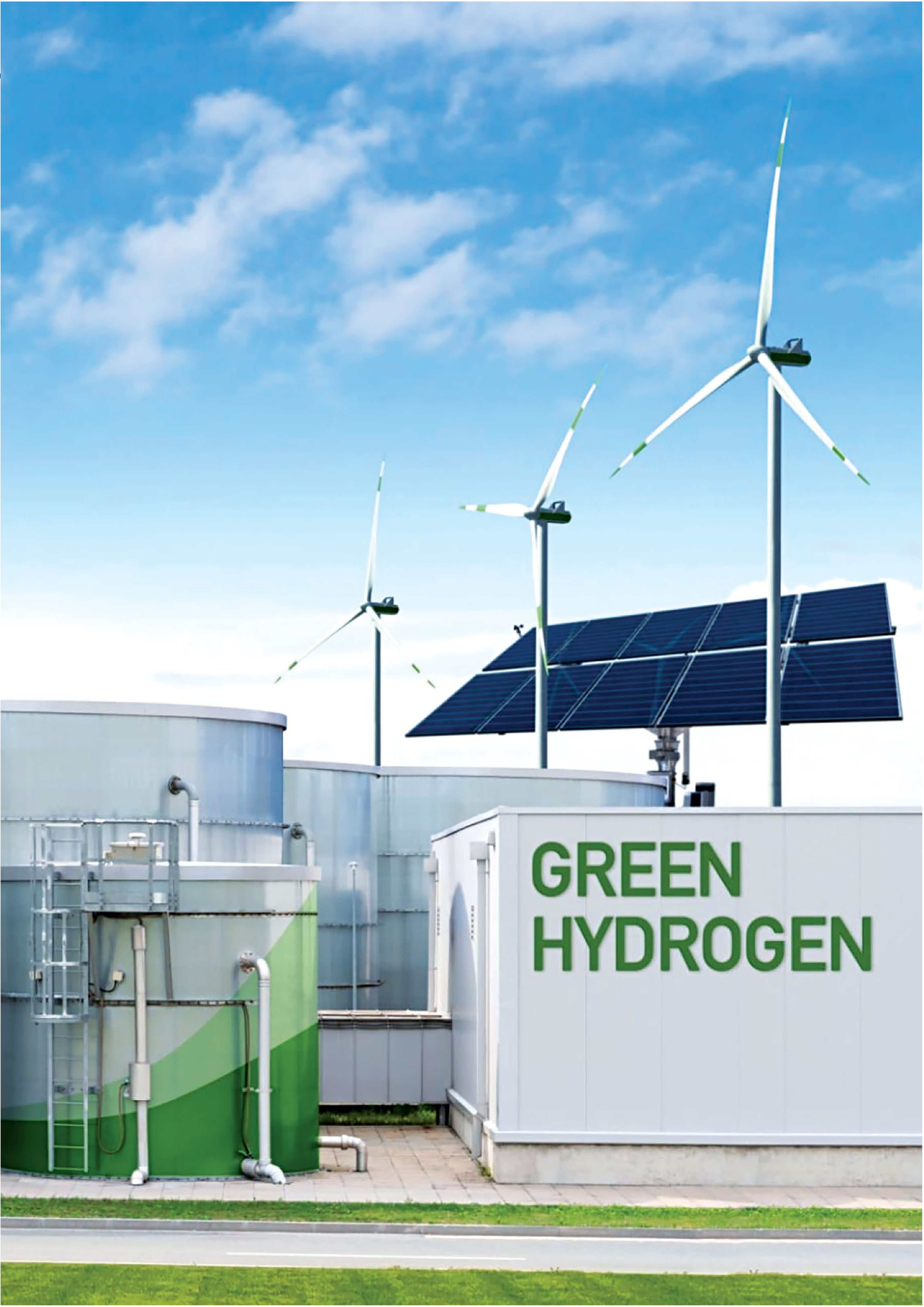
The National Green Hydrogen Mission and India's biggest challenge

To achieve energy independence around the centennial year of independence, India is considering hydrogen's application across several sectors (apart from renewables). Hydrogen, especially green hydrogen, is considered a promising alternative and a key transition fuel.

The National Green Hydrogen Mission envisions India to be a leading manufacturer and a major hub for green hydrogen in the world. It has also laid out an initial plan of action to increase the green hydrogen production capacity in the country to about 5 Mt per annum (*National Green Hydrogen Mission*, 2023), thereby abating over 50 Mt of annual GHG emissions. This would mean that India will develop a green hydrogen ecosystem of producers and consumers that is self-sufficient and enables the country to export green hydrogen globally.

However, India lacks the necessary infrastructure and some of the key technologies that are needed to realise these goals. India does not produce green hydrogen at a commercial stage at present and lacks several raw materials (critical minerals) that are required to manufacture electrolysers. It does not inherit an effective hydrogen transportation and storage infrastructure and does not have additional/excess renewable energy infrastructure for green hydrogen generation.

A functioning hydrogen economy requires a lot of additional infrastructure, which is expensive. Hence, we need a framework that prioritises hydrogen demand centres throughout the country. This will pave the way for the strategic utilisation of raw materials and infrastructure, thereby tapping into India's fullest potential for clean hydrogen production and making us self-reliant.


GREEN
HYDROGEN

The Hydrogen Applications Segmentation and Hierarchy Framework

The need for a hierarchy

Because the entire infrastructure around a hydrogen economy is relatively expensive today, a hierarchical approach is necessary to prioritise hydrogen usage across various sectors. It can help identify key sectors where hydrogen can have a significant impact while recognising areas where other alternatives may be more beneficial.

The 'Clean Hydrogen Ladder' developed by Michael Liebreich (2021), CEO of Liebreich Associates, is an example of such an approach that prioritises and ranks hydrogen applications, ranging from areas where hydrogen usage is inevitable to areas where it is not competitive from a market standpoint.

Similar work has been done by the Department of Energy (DOE), U.S. Government, which takes a qualitative approach (Murdoch et al., 2023). In another work, Kufeoglu (2023) analysed 20 different hydrogen applications and business models of 64 different companies to identify the most immediately deployable applications and distant applications that may become plausible in the future.

The Hydrogen Applications Segmentation and Hierarchy (HASH) framework presents a comparable endeavour for India, which is still in its nascent phase in establishing a hydrogen ecosystem. The aim is to determine the sectors where hydrogen applications can be prioritised and those where alternative solutions can be explored.

The HASH algorithm and methodology

The HASH framework has been developed keeping in mind the advantages and shortcomings of hydrogen (both as a fuel and feedstock) to prioritise its use across different sectors. It uses a rational methodology to prioritise sectors that have an impact on reducing emissions using hydrogen and sectors that are involved in hydrogen production. HASH utilises multiple criteria (see Figure 2) to identify and rank sectors, from the most suitable application of hydrogen, which will be the major narrative around the hydrogen ecosystem in India, to the least significant application, which is less likely to be competitive in the market.

Analytical methodology of HASH

In this work, a simplified approach has been undertaken to rank sectors in a hierarchical manner to identify the most suitable and least competitive avenue for hydrogen application.

Let us assume that there are *n* criteria that influence the hydrogen application in any given sector. Let each criterion be represented as X, i.e., X_1, X_2, X_3, … X_n.

Now assume that each sector can be given only one of the three ratings—maximum, moderate, or minimum—for each criterion. In other words, the rating that a sector can score for a criterion is a subset of three numbers, for example, {3,2,1}/{10, 5,1}/{9,5,1}.

A sector that is most suitable for a hydrogen application would score maximum in all the criteria. Therefore, it can be referred to as the ideal sector. Therefore, the score of the ideal sector would be as follows:

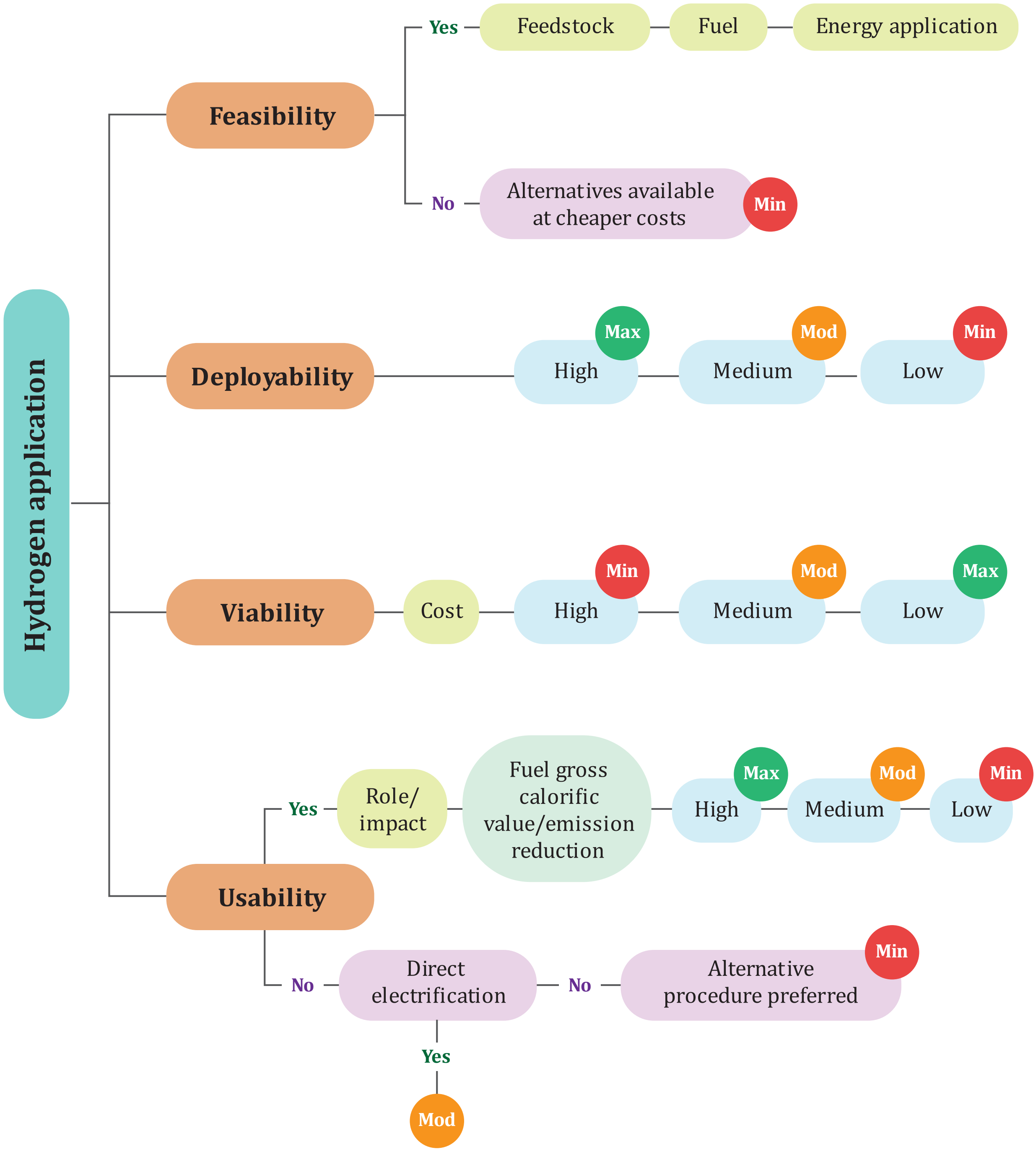
Ideal sector = Maxima [$\sum_{i=1}^{n}(X_i)$], where n = number of chosen criteria.

This can be taken as the baseline to compare the other sectors. Hence, for the other sectors, the score would be as follows:

Sector score = $\sum_{i=1}^{n}(X_i)_{Score}$

Therefore, the final rating (out to 1) that a sector would receive will be the ratio of the sector score to that of the ideal sector score:

Final sector rating = $\frac{\sum_{i=1}^{n}(X_i)_{Score}}{Maxima\left[\sum_{i=1}^{n}(X_i)\right]}$



Max **Maximum rating:** When hydrogen best suits the scenario for the application of choice

Mod **Moderate rating:** When alternatives such as biomass, renewables, and batteries are available and warrant detailed evaluation

Min **Minimum rating:** When alternatives such as coal, batteries, and natural gas are strongly preferred over hydrogen

Figure 2: The HASH algorithm

The framework employs six distinct criteria to evaluate the potential of hydrogen utilisation:

- Feasibility for feedstock, fuel, or energy storage
- Availability of alternatives
- Deployability, as indicated by the technology readiness level
- Availability in terms of cost
- Usability and impact
- Potential for process electrification

Utilising multi-criteria decision-making methods (MCDM), HASH prioritises 20 distinct sectors or applications for hydrogen usage, classifying them into four tiers based on their level of competitiveness. Within each tier, priority is given to the most significant hydrogen applications (see Figure 2).

Recommendation: The HASH Framework

The HASH framework provides valuable insights into key drivers of a hydrogen ecosystem in India, highlighting sectors that should be prioritised for investment. Furthermore, it identifies areas where hydrogen applications are not feasible, allowing for efficient allocation of resources (see Figure 3).

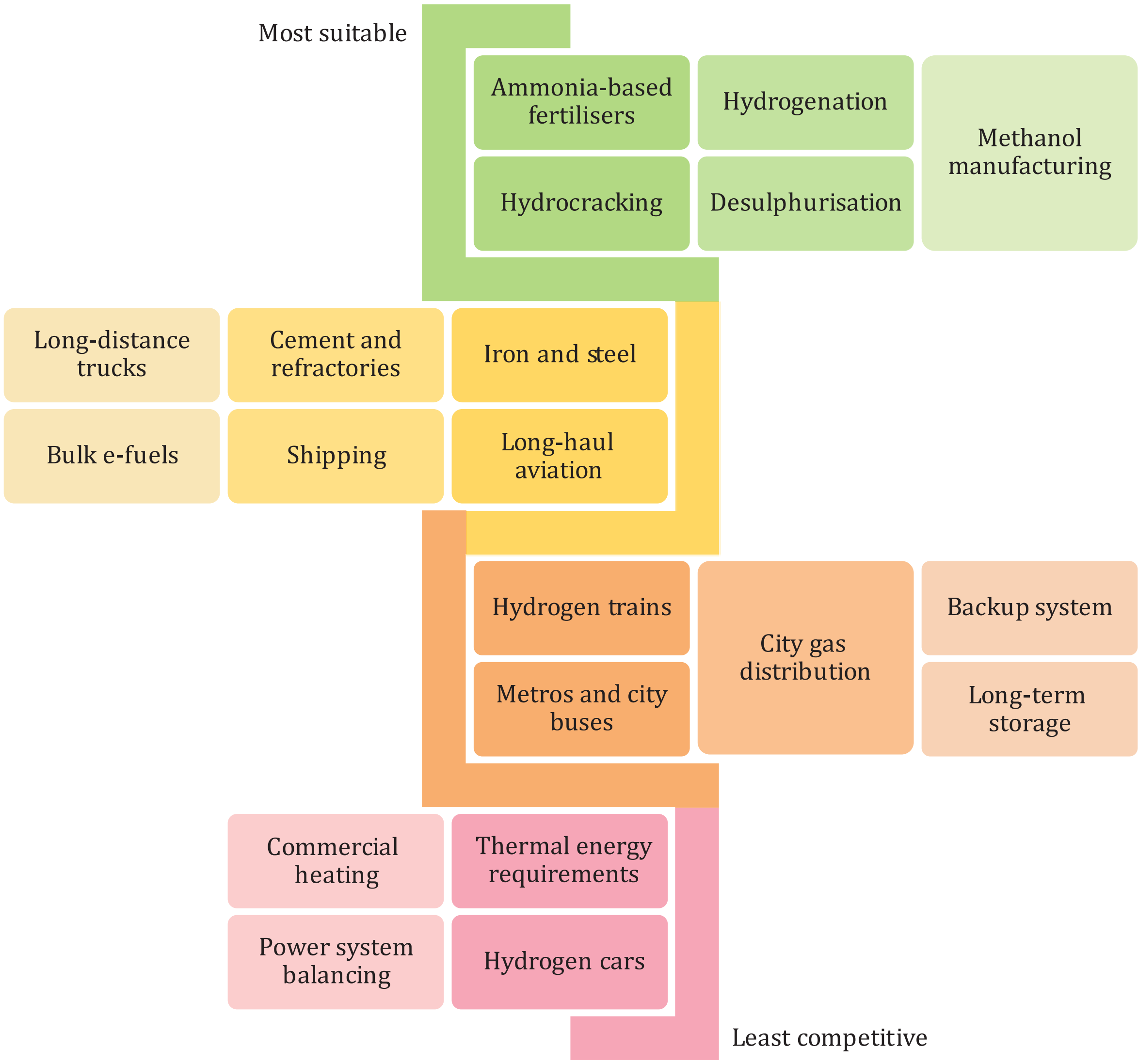
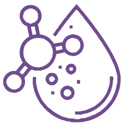


Figure 3: The HASH framework

Based on the findings, it can be concluded that a hydrogen application as a feedstock—such as ammonia-based fertilisers, hydrogenation, desulphurisation, hydrocracking, and methanol synthesis—will be the primary driver of the hydrogen narrative in the country in the near future until a level of parity is reached with respect to cost. On the other hand, hydrogen-powered cars and other energy applications are less likely to contribute and should, therefore, receive comparatively less attention.

The sector-wise impact of hydrogen application is listed below.

Feedstock

Sector	Impact of hydrogen
 **Ammonia-based fertilisers**	• Ammonia is one of the most important sources of nitrogen for plants and is used to make fertilisers. • About 0.180 kg of hydrogen is used for manufacturing 1 kg of ammonia (Nallapaaneni & Sood, 2022). • **No other alternatives are available.**
 **Hydrocracking**	• Mainly utilised in refineries for cracking of heavier petroleum fractions to lighter products • Hydrogen is used in a two-stage process where about 0.042 kg (*Hydrocracking Is an Important Source of Diesel and Jet Fuel*, 2013) of hydrogen can be used for cracking 1 kg feed. • **No other alternatives are available.**
 **Hydrogenation**	• Hydrogen molecules are added for the saturation of unsaturated compounds. • Hydrogenation of vegetable oil requires about 0.005 kg of hydrogen (Baharudin & Watson, 2017; Savchenko & Makaryan, 1999) for every kg of the product. • **No other alternatives are available.**
 **Desulphurisation**	• Sulphur is removed from refinery oils by treating it with hydrogen to form dihydrogen sulphide (H_2S) gas. • About 0.057 kg of hydrogen (*The Role of Hydrogen in Removing Sulfur from Liquid Fuels*, 2017) is utilised to remove about 1 kg of sulphur. • **No other alternatives are available.**

Feedstock

Sector	Impact of hydrogen
Methanol manufacturing	• Hydrogen acts as a reducing agent as syngas gets reduced to methane and reacts with hydrogen to form methanol. • About 0.189 kg of hydrogen (Martín & Grossmann, 2017; Schorn et al., 2021) is required to produce 1 kg of methanol. • **Biomass is an alternative that can be used, but the process yields less methanol and is energy intensive.**
E- fuels	• Direct capture of CO_2 from the air to react with green hydrogen to form fuels such as methanol and kerosene • **Highly expensive**
Iron and steel sector	• Hydrogen can directly reduce haematite to sponge iron, or it can also be blended with natural gas or coal to reduce iron ore, which can be later converted to steel in an electric arc furnace. • It can also help achieve high temperatures within a furnace. • About 0.06 kg of hydrogen (Bhaskar et al., 2021) is required to produce 1 kg of crude steel. • **No other clean alternatives are available.**

Fuel

Sector	Impact of hydrogen
Large aviation	• High energy density and lightweight of hydrogen make it a great choice for long-haul flights. • Hydrogen is a clean fuel with zero emissions when combusted. • **No other lightweight fuels are available.**
Cement and refractories	• Hydrogen can be used to replace coal, which is used as fuel, or it can be blended with coal or natural gas to reach the high temperatures required in a cement rotary kiln (>1000°C). • About 0.024 kg of hydrogen is required to produce about 1 kg of cement. • **Electrification of kilns is possible but highly expensive; alternative fuels such as biomass can be utilised.**
Shipping	• Hydrogen has the potential to replace marine diesel oil and heavy fuel oil that release a large amount of CO_2 emissions during combustion. • **No other significant alternatives**
Long-distance and heavy-duty trucks	• Hydrogen has a very high energy density. • Hydrogen fuel-cell vehicles offer longer range and shorter refuelling time for heavy-duty trucks. • Silent operation and zero emissions • **Batteries with larger energy storage capacities can become potential alternatives.**
City gas distribution	• Hydrogen and natural gas blends can replace pure natural gas in pipelines that are used for domestic applications. • Reduction in carbon footprint • **Can result in a reduction of energy transfer and increased energy requirement for commutation**

Fuel

Sector	Impact of hydrogen
Trains	• Hydrogen locomotives that run on fuel cells can replace diesel locomotives that run in remote regions and hilly terrains. • **Direct electrification is always possible.**
Metros and city buses	• Hydrogen fuel-cell–based vehicles have a silent operation and are emission-free. • **Lithium battery alternatives are available.**
Thermal requirements in industries	• Hydrogen is a clean fuel and has 4–5 times more energy content than coal. • **Resistive heating using electrical energy is an alternative.**
Cars	• Hydrogen fuel-cell–based cars and hydrogen direct combustion engine–based cars are being developed as alternatives to conventional vehicles. • **Battery electric vehicles are a clean alternative.**
Commercial heating	• Hydrogen can be explored for commercial heating applications such as space heating and water heating. • **Resistive heating using electrical energy is an alternative.**

Energy application

Sector	Impact of hydrogen
 Backup systems	• Hydrogen can act as an excellent backup fuel because of its longer shelf life and higher energy content. • **Larger battery systems with high energy densities can be better alternatives.**
 Power systems balancing	• The excess energy from renewable systems can be stored using hydrogen and later utilised by direct combustion or fuel cells. • **Battery systems are alternatives.**
 Long-term storage	• Because of its longer shelf life, hydrogen can be used as long-term batteries if stored under the required conditions. • **No alternatives are available at present.** • **Expensive mode of energy storage**

Limitations and Future Work

HASH is an ex ante framework that provides a qualitative narrative of major sectors where hydrogen application is thermodynamically possible. The current version of the HASH framework does not consider practical constraints and societal implications inherent in each sector. Analyses of the impact of hydrogen technology on job opportunities, socio-economic factors, macroeconomic considerations, geopolitical factors, safety, and associated carbon footprint are absent. The framework also excludes discussions on necessary investments and key market players (availability) and their roles (with and without government interventions) in advancing a hydrogen economy.

An advanced HASH framework will be the next step for us where additional considerations related to India's socio-economic position, regional diversity, import and export capabilities, resource availability, major market players, and other relevant factors can be integrated into the MCDM methodology. Each of these criteria should be weighted appropriately, considering their individual significance. In addition, the different sectors under consideration should also be weighted appropriately to avoid ambiguity or perceived bias. For instance, given India's status as the world's largest manufacturer of direct reduced iron (DRI) and the development of hydrogen-based DRI processes, such as hydrogen breakthrough ironmaking technologies (HYBRIT), it would be reasonable to prioritise hydrogen-based iron and steel-making over cement and refractories, where hydrogen's role is primarily as a fuel.

The framework must also consider India's dynamic energy landscape, such as the increasing number of renewable energy sources and their falling prices. A lot of heating applications can tend to pivot towards electrification. Hence, appropriate electricity and cost projections must also be considered.

Hydrogen has immense potential as a clean and versatile resource. With the availability of abundant renewable energy resources—such as solar and wind—and the increasing focus on green hydrogen production, India is well-positioned to leverage this technology to achieve its climate and sustainable development goals. With proper rationalising of resources and prioritising of demand centres, the country has a unique opportunity to establish itself as a global leader in hydrogen—driving innovation, creating new job opportunities, contributing to a cleaner and more prosperous future, and becoming truly *Aatma Nirbhar*.

References

Baharudin, L., & Watson, M. (2017). Hydrogen applications and research activities in its production routes through catalytic hydrocarbon conversion. *Reviews in Chemical Engineering*, *34*. https://doi.org/10.1515/revce-2016-0040

Bhaskar, A., Assadi, M., & Somehsaraei, H. N. (2021). Can methane pyrolysis based hydrogen production lead to the decarbonisation of iron and steel industry? *Energy Conversion and Management: X*, *10*, 100079. https://doi.org/10.1016/j.ecmx.2021.100079

Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P.-S. (2022). Strategies to achieve a carbon neutral society: A review. *Environmental Chemistry Letters*, *20*(4), 2277–2310. https://doi.org/10.1007/s10311-022-01435-8

Energy statistics India. (2023). https://www.mospi.gov.in/sites/default/files/publication_reports/Energy_Statistics_2023/EnergyStatisticsIndia2023.pdf

Erbach, G., & Jensen, L. (2021). *EU hydrogen policy*. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689332/EPRS_BRI(2021)689332_EN.pdf

Hertwich, E. G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F. N., Olivetti, E., Pauliuk, S., Tu, Q., & Wolfram, P. (2019). Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—A review. *Environmental Research Letters*, *14*(4), 043004. https://doi.org/10.1088/1748-9326/ab0fe3

Hydrocracking is an important source of diesel and jet fuel. (2013, January 18). https://www.eia.gov/todayinenergy/detail.php?id=9650

India's stand at COP-26. (2022, February 3). https://pib.gov.in/pib.gov.in/Pressreleaseshare.aspx?PRID=1795071

Kufeoglu, S. (2023). *From hydrogen hype to hydrogen reality: A horizon scanning for the business opportunities*. C-EENRG.

Martín, M., & Grossmann, I. E. (2017). Towards zero CO2 emissions in the production of methanol from switchgrass. CO2 to methanol. *Computers & Chemical Engineering*, *105*, 308–316. https://doi.org/10.1016/j.compchemeng.2016.11.030

Murdoch, H., Munster, J., Satyapal, S., Rustagi, N., Penev, M., Elgowainy, A., Crane, D., Cummins, K., Klembara, M., Chan, V., Tian, L., Shah, J., & Wagner, J. (2023). *Pathways to commercial liftoff: Clean hydrogen*. https://t.co/jyaIzKncI4

Nallapaaneni, A., & Sood, S. (2022, October 4). *Emission reduction potential of green hydrogen in ammonia synthesis for fertilizer industry*. WRI India. https://wri-india.org/blog/emission-reduction-potential-green-hydrogen-ammonia-synthesis-fertilizer-industry

National Green Hydrogen Mission. (2023, March 6). https://www.india.gov.in/spotlight/national-green-hydrogen-mission

Power sector at a glance all India. (2023, March 31). https://powermin.gov.in/en/content/power-sector-glance-all-india

Ritchie, H., Roser, M., & Rosado, P. (2020). CO_2 and Greenhouse Gas Emissions. *Our World in Data*. https://ourworldindata.org/emissions-by-fuel

Savchenko, V. I., & Makaryan, I. A. (1999). Palladium catalyst for the production of pure margarine: Catalyst and new non-filtration technology improve production and quality. *Platinum Metals Review, 43*, (2), 74–82. https://www.ingentaconnect.com/content/matthey/pmr/1999/00000043/00000002/art00011?crawler=true&mimetype=application/pdf

Schorn, F., Breuer, J. L., Samsun, R. C., Schnorbus, T., Heuser, B., Peters, R., & Stolten, D. (2021). Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations. *Advances in Applied Energy*, *3*, 100050. https://doi.org/10.1016/j.adapen.2021.100050

Liebreich, M. (2021, August 15). *The clean hydrogen ladder*. LinkedIn. https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/

The role of hydrogen in removing sulfur from liquid fuels. (2017). https://www.linde.com/-/media/linde/merger/documents/sustainable-development/the-role-of-hydrogen-in-removing-sulfur-from-liquid-fuels-w-disclaimer-r1.pdf?la=en

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